HEAT TREATMENT OF SRF CAVITIES IN A LOW-PRESSURE ATMOSPHERE*

D. Gonnella, F. Furuta, and M. Liepe, CLASSE, Cornell University, Ithaca, NY 14853

Abstract

Recent results from FNAL on baking superconducting RF cavities at high temperatures in a low-pressure atmosphere of a few mTorr indicate that such treatments can increase the medium field quality factor. A cavity was prepared at Cornell by high temperature heat treatment both in vacuum and in a low pressure nitrogen atmosphere. Nitrogen treatment was found to cause an increase in energy gap and desirable changes to the BCS material properties of the surface layer, which in turn caused a decrease in BCS resistance. We observe a small increase in Q with increasing accelerating field in the medium field region following nitrogen treatment and light EP between 2.1 and 2.5 K.

INTRODUCTION

In recent years, superconducting RF cavities have become the dominant driving force in modern particle accelerators. A Future CW machines such as the Cornell Energy Recovery Linac (ERL) require many cavities to operate at a high Q_0 in the medium field region. Therefore, developing cavities that have the highest Q at medium field is crucial to this goal. Fermi National Accelerator Lab (FNAL) has recently demonstrated an increasing quality factor with field (anti-slope) in the medium field region after baking cavities at high temperatures in a low pressure atmosphere of nitrogen or argon [1]. In this paper we discuss a recent cavity prepared at Cornell using a similar method and the results of the test. We especially compare the performance of a vacuum heat treated in vacuum with the performance after heat treatment in a low pressure nitrogen atmosphere at the same temperature.

CAVITY PREPARATION AND TESTING

A 1.3 GHz single-cell Cornell ERL shape cavity was manufactured from fine-grain niobium of RRR 300. It was given a 100 μm EP and heat treated for 2 days at 650°C. It was then given 5 μm EP and tested to provide a baseline measurement. The cavity then received the following additional preparation steps with tests in between: an 800°C heat treatment for 3 hours in vacuum; 5 μm EP; 15 μm EP and 800°C heat treatment for 3 hours in vacuum plus 10 minutes in an atmosphere of 1×10^{-2} Torr of N_2; and 7 μm EP. At each step, Q_0 vs E at various temperatures between 1.6 and 4.2 K, Q_0 vs temperature at low fields, and resonance frequency vs temperature was measured. The 2.0 K Q_0 vs E curves for each test is shown in Fig. 1. With each successive step except immediately after the N_2 treatment, the 2.0 K Q increased from the previous test. Immediately after N_2 treatment, the Q_0 at all temperatures was on the order of 1×10^8, suggesting the surface layer was contaminated. We theorize that NbN in the wrong phase formed on the surface, causing high surface resistance. Additional 7μm EP was sufficient to remove this high resistance surface layer. Comparing the two 800°C heat treatments with and without nitrogen atmosphere followed by brief chemistry demonstrates flat Q_0 vs E performance in the medium field region with similar values at 2.0 K. However, separating out the BCS resistance and residual resistance shows noticeable differences between the two tests as will be pointed out in the next section.

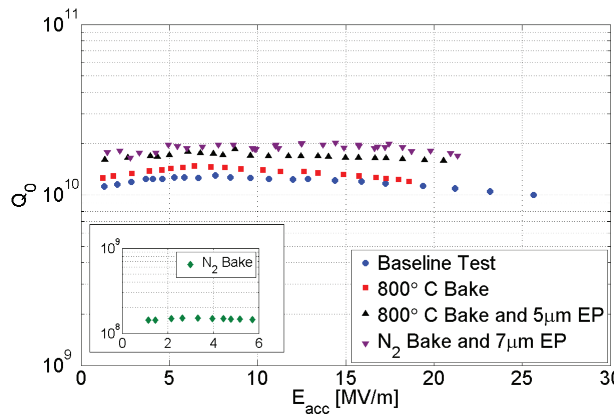

Figure 1: Q_0 vs E performance at 2.0 K for all tests. Error bars on Q_0 are 20 % while error bars on E_{acc} are 10 %.

The final test, after N_2 treatment and 7 μm EP is of the most interest with respect to testing done at FNAL. Similar preparation at FNAL has produced anti-slope in the 2.0 K Q_0 curves [2]. The Q_0 vs E performance for our cavity at different temperatures is shown in Fig. 2. We observe that the Q_0 between 5 and 17 MV/m is flat at most temperatures including 2.0 K. However in the 2.1 to 2.5 K temperature region, the Q_0 does increase slightly with field up to 15 MV/m. Accordingly, anti-slope was observed in our nitrogen heat treatment cavity though interestingly at a different temperature range than in the FNAL treated cavity.

SURFACE RESISTANCE ANALYSIS

From the Q_0 vs E data at varying temperatures between 1.6 and 2.1 K, the residual resistance and 2.0 K BCS resistance was found as a function of accelerating field for each material preparation step except for immediately after the N_2 treatment. The BCS resistance at 2.0 K as a function of field can be extracted from the total surface resistance at 2.0 K and the residual resistance as a function of field [3].

* Work supported by DOE Grant DE-SC0002329

ISBN 978-3-95450-143-4

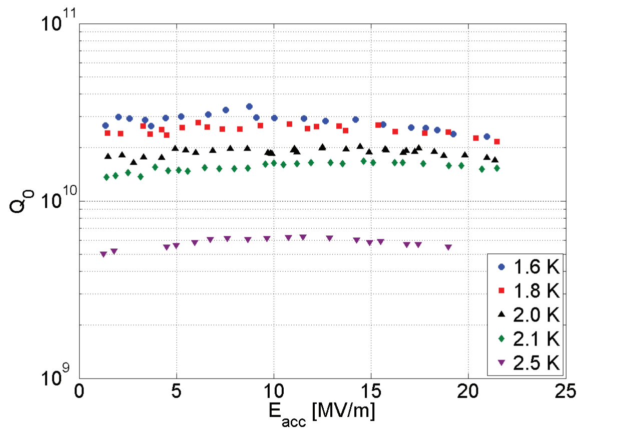

Figure 2: Q_0 vs E performance after N_2 treatment and 7 μm EP. Error bars on Q_0 are 20 % while error bars on E_{acc} are 10 %.

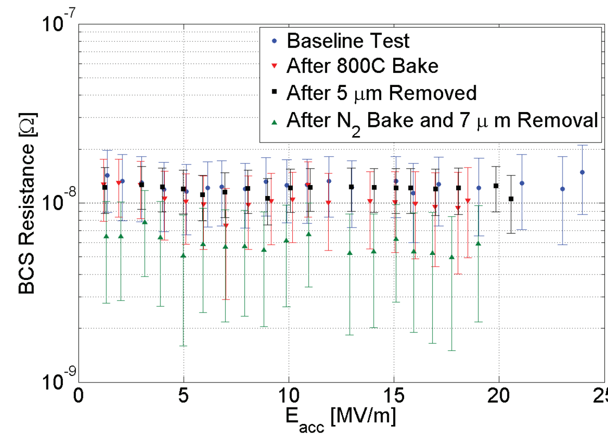

Figure 4: BCS resistance at 2.0 K as a function of field for each material preparation step except immediately after N_2 treatment.

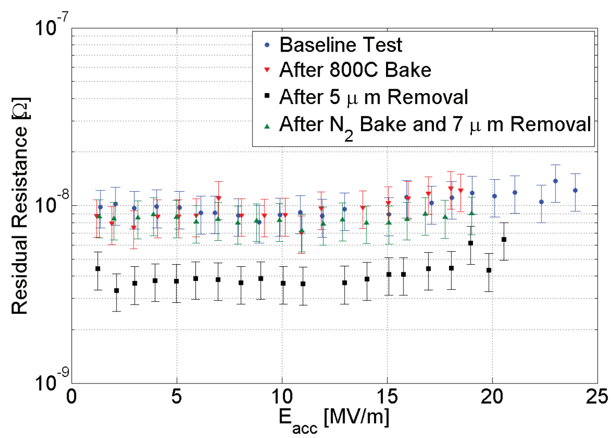

Figure 3: Residual resistance as a function of accelerating field for each material preparation step except immediately after N_2 treatment, which was power limited.

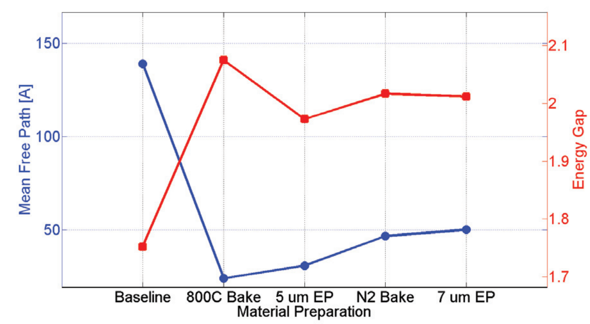

Figure 5: Mean free path and energy gap as a function of material preparation.

This data is shown in Fig. 3 and Fig. 4. In general, both the residual and 2.0 K BCS resistance show only a weak field dependence. Q slope above 17 MV/m is caused by a small increase in residual resistance. It is clear from Fig. 3 that the residual resistance is significantly lower after heat treatment in vacuum and 5 μm EP but increased again after N_2 treatment.

The BCS surface resistance decreased by about 30% after the nitrogen treatment, keeping the surface resistance constant, manifesting in nearly identical Q curves in Fig. 1. The N_2 treatment thus has caused an increase in residual resistance and a decrease in BCS resistance.

MATERIAL PROPERTIES

Resonance frequency vs temperature and Q_0 vs temperature can be fit by using SRIMP to solve BCS theory [4]. T_C, energy gap ($\Delta/k_B T_C$), mean free path, and residual resistance (R_{res}) were found at each step using the method described in [3]. From the mean free path, the Ginzburg-Landau constant κ_{GL} and the lower critical field B_{c1} can be calculated. The material properties and calculated parameters are listed in table 1 for each cavity preparation step.

A plot of mean free path and energy gap as a function of material preparation is shown in Fig. 5. The heat treatment in vacuum caused the mean free path to strongly decrease and the energy gap to increase. It is clear that the nitrogen treatment caused the small changes in the mean free path, energy gap, and T_C. Even immediately after nitrogen treatment with no chemistry, the BCS properties are very similar to after 7 μm EP except for the residual resistance, which is very high. The decrease in BCS resistance between vacuum heat treatment and nitrogen treatment is thus caused by small, desirable changes in the energy gap, critical temperature, and mean free path. For all tests, the lower critical field, B_{c1} was found to have no correlation to quench or Q slope, consistent with measurements in [3] and [2].

Table 1: Summary of Extracted Material Properties

Property	Baseline	After 800°C	After 5 μm EP	After N_2 Treatment	After 7 μm EP
T_c [K]	9.2 ± 0.9	9.1 ± 0.9	9.0 ± 0.9	9.2 ± 0.9	9.2 ± 0.9
$\Delta/k_B T_C$	1.75 ± 0.02	2.08 ± 0.03	1.97 ± 0.03	2.02 ± 0.03	2.01 ± 0.03
Mean Free Path [nm]	14 ± 4	2.4 ± 0.7	3.1 ± 0.9	5 ± 1	5 ± 1.5
R_{res} [nΩ]	9 ± 2	12 ± 3	4 ± 1	1800 ± 400	2.0 ± 0.8
κ_{GL}	5.0 ± 0.8	22 ± 5	17 ± 4	12 ± 2	11 ± 2
B_{c1} [mT]	58 ± 12	22 ± 19	26 ± 18	33 ± 16	34 ± 16

CONCLUSION

A single-cell SRF cavity was prepared by EP and given a series of heat treatments in vacuum and low-pressure nitrogen atmosphere and additional chemistry. The bake in vacuum plus 5 μm EP caused a decrease in residual resistance while the N_2 treatment plus 7 μm EP caused an increase in residual resistance and a decrease in BCS resistance at 2.0 K. The decreased BCS resistance was caused by small, desirable changes in energy gap, T_C, and the mean free path of the RF surface layer. After nitrogen treatment and EP, a small anti-slope was observed between 2.1 and 2.5 K, however anti-slope at 2.0 K such as seen at FNAL was not found. In each material preparation step (with the exception of immediately after N_2 treatment which was power limited), the cavity exceeded the lower critical field B_{c1} without any noticeable Q degradation.

We have demonstrated reduction in the medium field Q slope by baking at high temperatures both in vacuum and in a low-pressure nitrogen atmosphere. This result is very promising for the consistent production of high-Q_0 cavities that are required for future CW machines such as the proposed Cornell ERL. Future work will involve varying the recipe of preparation to further explore the effect of baking in atmosphere.

ACKNOWLEDGMENTS

The authors would like to thank Sam Posen and Daniel Hall for assistance during cavity assembly and testing and Nicholas Valles for useful discussions about SRIMP. We would also like to thank the CLASSE support staff for assistance during chemistry and cavity preparation especially John Kaufman, Brendan Elmore, Holly Conklin, and Terri Grubber.

REFERENCES

[1] A. Grassellino and A. Romanenko, et. al. “Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures,” ArXiv e-prints, 1206.0288, June 2013.

[2] D. Gonnella, M. Liepe, and A. Grassellino, “Performance of a FNAL Nitrogen Treated Superconducting Niobium Cavity at Cornell,” Proceedings of SRF 2013 (2013).

[3] D. Gonnella and M. Liepe, “High Q0 Studies at Cornell,” Proceedings of SRF 2013 (2013).

[4] J. Halbritter, “FORTRAN-Program for the Computation of the Surface Impedance of Superconductors.” KAROLA Externer Bericht 3/70-6 (1970).

ISBN 978-3-95450-143-4